Detlef Burchard, Dipl.-Ing., Box 14426, Nairobi, Kenya

Frequency Doubling using Semi-Conductor Diodes

At low input voltages, every rectifier circuit has an area where there is a quadratic relationship between the output quantity and the input quantity. One use for this ratio is the measurement of the power or the root mean square value as carried out, for example, in (2). Another application is frequency doubling, which is the subject of this article.

1.
FUNDAMENTAL PRINCIPLES

Semi-conductor diodes have in general exponential voltage-current characteristics. This can be used directly to derive a quadratic relationship for the rectified current at input voltages of below $2 \cdot U_T$ (U_T temperature voltage 25 to 50mV). The relationships are explained in more detail in (1). The following formula is also obtained from the same literature:

$$\frac{I}{I_S} = \frac{\hat{U}}{U_T} \sin\Omega t + \frac{1}{4} \frac{\hat{U}^2}{U_T^2} - \frac{1}{4} \frac{\hat{U}^2}{U_T^2} \cos2\Omega t \quad (1)$$

For a sinusoidal diode with the amplitude $\hat{U}$, the standardised diode current I/I_S has essentially three terms: the first, with the input frequency, which increases linearly with the input voltage; the second, which corresponds to the rectified current and increases quadratically with the input voltage; and the third, which is an alternating current with a doubled frequency (2Ω) and with an amplitude equal to the rectified current. It is this third term which is of interest to us here. It also increases quadratically with the input voltage.

The first term, the input frequency fraction, can theoretically be made to vanish by means of a push-pull arrangement using two diodes. In practise, of course, this is not completely successful. However, it is relatively easy to ensure that the doubled input frequency emerges from the output at least ten times stronger than any other fraction.
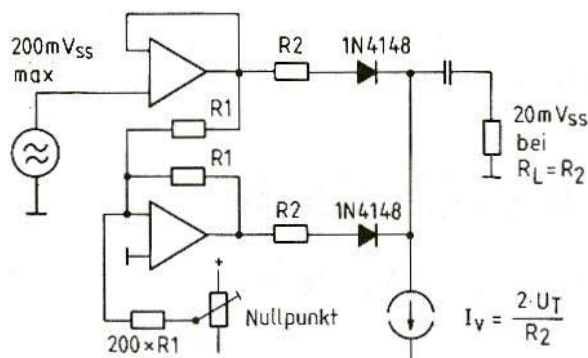
Fig.1:
Low-Frequency
Frequency Doubler

Nullpunk = Zero point
bei = at

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According to (1), the e.m.f. of the doubled frequency generated is independent of the type of diode and the point of operation. By contrast, the internal resistance at which this e.m.f. is available changes very considerably with the type of diode and the semiconductor material. Without a bias current, the internal resistance of Si diodes will be a few hundred megOhms, a few megOhms for Schottky diodes, and a few tens of kiloOhms for Ge diodes. The figures apply to small-signal diodes. In high-frequency circuits we would like lower Ohm values, right down to 50Ω, in order to match to a system impedance. This is possible if a suitable bias current is selected. In general, the AC resistance in the area of exponential voltage-current ratio is expressed by:

$$R_\sim = \frac{U_t}{I_v} \qquad (2)$$

For the desired value of 50Ω, then I_v = 0.6mA. If we now look at the curves contained in (1), we discover that such bias currents are possible only using Schottky diodes. Ge diodes leave the exponential area above about 100µA. The border between Schottky diodes and Si diodes even earlier, at 10µA (1N4148). Other universal Si diodes go somewhat further: 1N4151 to 30µA and 1N4448 to 100µA. The border between Schottky diodes and Si diodes lies at the point where 50Ω technology begins, i.e. perhaps between 1 MHz and 10 MHz. Ge diodes are not required, unless we want to mange without a bias current.

2.
CIRCUITS

The frequency doubling circuit using semi-conductor diodes is in no way different from a rectifier circuit. Instead of the DC the AC is now coupled out. Fig.1 shows a circuit suitable from audio to radio frequencies, in which the input-side phase reversal and isolation of the source is carried out by operational amplifiers. The offset voltages of
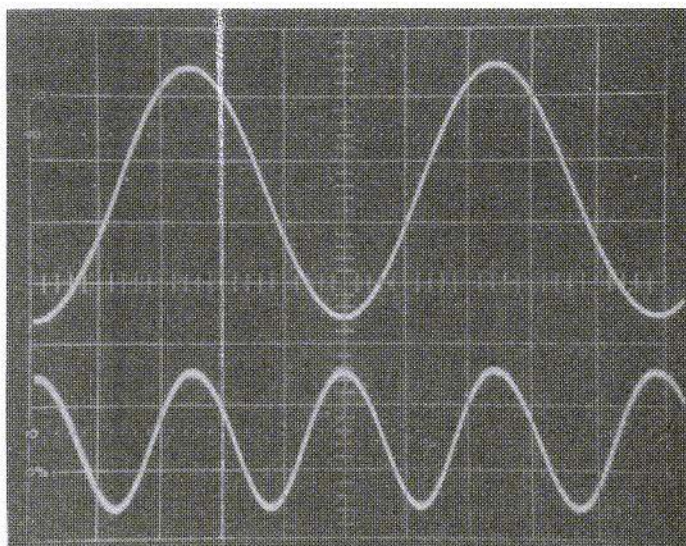
Fig.2:   Input and Output Signals of Circuit in Fig.1
         X: 0.2 µs/div; Y1: 50mV/div; Y2: 10mV/div
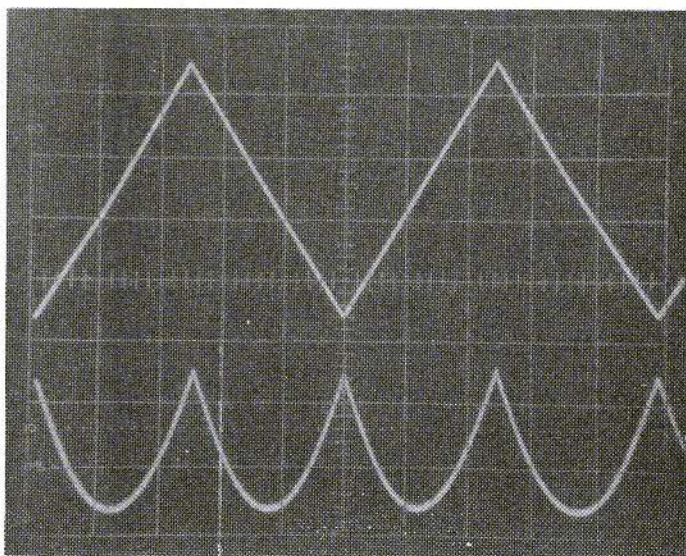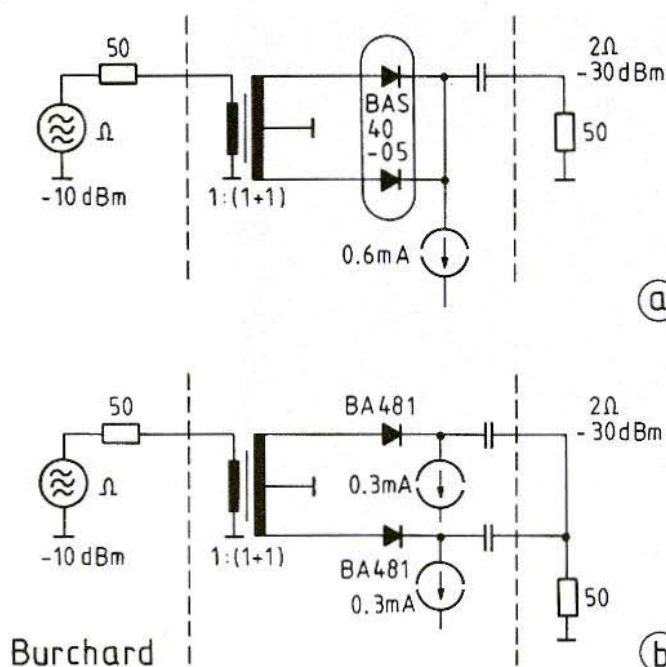
Fig.3:   As Fig.2, but with Delta-Form Input

Fig.4:
High-Frequency
Frequency Doubler
a. With a Diode
   Pair
b. With Individual
   Diodes which
   do not have
   Identical
   Characteristics

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the amplifiers and the variations in the diodes are balanced out by the zero preset. The resistances R2 prevent protect against low loads for the amplifiers. They would be selected to be between a few hundred Ohms and a few kiloOhms. If the load resistance $R_L = R_2$, the best power matching is obtained using the bias current marked up I_V. For idle operation, we naturally obtain double the output voltage, and then the bias current is not at all critical. Nor is any special current source required for the bias current. A resistor to the negative operating voltage of the operational amplifier is fully sufficient.

Fig.2 shows how well this doubler operates and how little distortion it produces. Here fast type LM361

opamps were used, so that even a signal of 1 MHz is still satisfactorily squared (Fig.3). Thus we have here a wide-band circuit, which functions from low frequencies right up to a higher limit determined by the opamp. For low distortion the input voltage of $200mV_{SS}$ should not be greatly exceeded and the bias current should be selected accordingly. We then obtain approximately $20mV_{SS}$ at the output, for power matching, and twice that for idle operation.

For frequencies higher than about 10 - 15 MHz there are no suitable operational amplifiers. A transformer is required for phase reversal now, so that finally a circuit like Fig.4a or b is obtained. It is also wide-band, and can be used in the HF, VHF and UHF ranges with a suitable transformer.
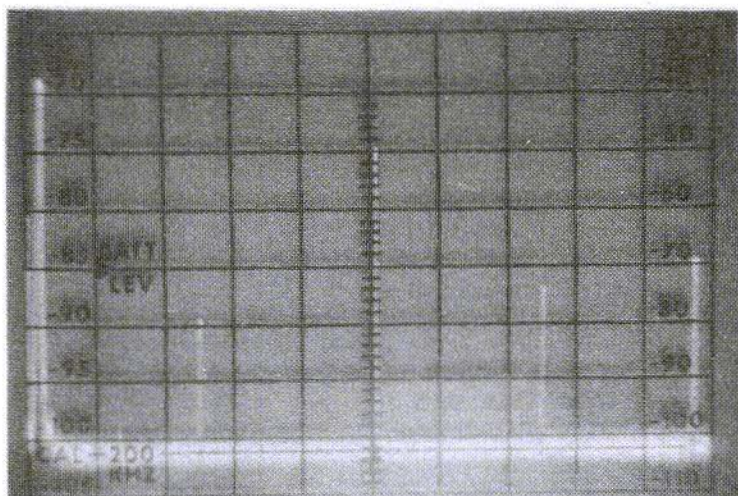
Fig.5: Output Spectrum of Fig.4b Circuit with 250 MHz/-10dBm at the Input
X: 100 MHz/div (0 to 1 GHz, zero marker on the left)
Y: 10dB/div (500 MHz line corresponds to -30dBm)

If the two diodes in a circuit are largely identical in their electrical properties, then the connections can be as in Fig.4a. However, a circuit like Fig.4b also functions with considerable discrepancies in the characteristics of the individual diodes.

The circuits are simple enough, and require only input power in the ranges which most signal generators can provide for them. A doubling circuit thus makes it possible to double the application tuning range of a measuring instrument. Many commercially available signal generators make use of this application for the top octave of their tuning range (3). Unfortunately, this also doubles the original noise deviation of the generator, and any amplitude modulation is distorted in accord-

ance with Fig.3, unless the modulator is positioned after the doubler.

Power matching is brought about by the selection of a suitable bias current. A 200Ω load should act at the output of the 1:(1+1) transformer. So each diode must have an AC resistance of 100Ω. This immediately results in output matching, for the diodes are parallel for the doubled frequency and the effective internal resistance is 50Ω. The bias current values given apply for U_T=30mV. Purists can vary the bias current until a VSWR optimum is obtained on the input and output sides, or until the optimum conversion efficiency is obtained. A degree of efficiency of 1% (conversion loss 20dB) is fairly typical for this circuit.

3.
FURTHER CHARACTERISTICS

Things are not ideal in technical reality. The input curve form is not ideally sinusoidal, the diodes are not completely identical and the characteristics are not exactly exponential.

However, it is not very difficult to obtain an output signal from such a doubler, which is 20dB or more better than all other output products.

Fig.5 shows the spectrum obtained if circuit Fig.4b is used, with a balanced-to-unbalanced transformer from the UHF input of a clapped-out television and the output voltage of a Marconi TF2015 signal generator. A spurious suppression of better than 20dB is thoroughly consistent with most high-frequency measurements on selective objects. Indeed, signal generators which can be purchased are often no better than this.

Because of the quadratic relationship the output rises twice as steeply as the input. This relationship is shown in Fig.6.

It is thus possible, without any problem, to set very low defined output voltages by varying the input power level. Only two special features need to be taken into account:

– If the precision with which the input level can be set is, for example, ±1dB, then the output error can not be smaller than ±2dB.
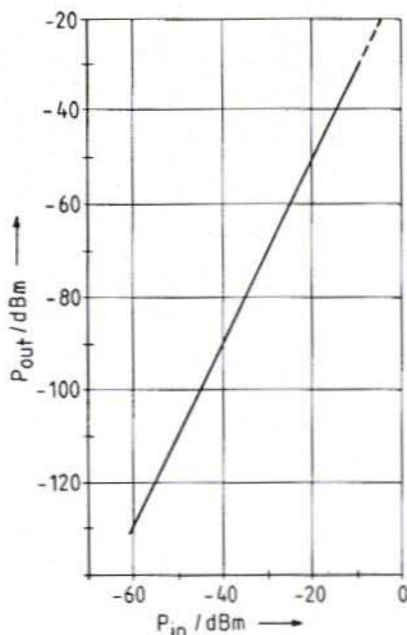

Fig.6: Relationship between Input and Output as per Fig.4

– Some spurious responses at the output do not decrease quadratically. So when the input power decreases, the suppression becomes worse. This can be remedied by an attenuator after the doubler.

4.
APPLICATIONS

I needed a doubler of this type to generate a defined input voltage for the meteorological satellite frequency (approximately 1.7 GHz). As I do not have a GHz signal generator this was the

only way to obtain a half-way exact measurement of the amplification of a converter I had purchased.

If we position a 20dB amplifier and another doubler after such a doubler, the frequency coverage can be even increased by a factor of 4. As the sweep of a frequency modulation is also multiplied accordingly, a circuit of this nature can be suitable for generating unusually large frequency sweeps. If necessary, we can mix back into the original frequency position using a fixed standby frequency.

Quadratic amplitude modulation might be of some interest for special purposes. I am happy to leave that for the future. If you want to avoid quadratic distortion and still modulate AM, a suitable modulator should be added to the doubler (e.g. PAS type from Mini-Circuits).
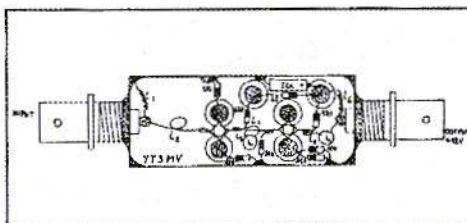
Because of the conversion losses of approximately 20dB and the differential frequencies at the input and output, the two gates of a doubler of this type are effectively decoupled. Matching to one is not spoilt by mismatching to the other. There is very little feedback to the drive generator.

If the generated signals are used to measure inter-modulation through a doubler, special care must be taken. The non-linearities can generate mixed products, which have nothing to do with the circuit to be tested.

5.
LITERATURE

(1) D. Burchard (1991): Basics of Rectification of Low AC Voltages using Semi-Conductor Diodes; VHF Communications 3/1991, pp.168-174.

(2) D. Burchard (1991): Absolute Calibration of a Noise Source; VHF Communications 2/1992, pp.76-89.

(3) N.N. (1987): Series 2022 Signal Generators Owners Manual, Marconi Instruments, Hertfordshire, U.K.